

# Particle and Nuclear Physics with High Energy Leptons

M W Krasny<sup>a</sup>

<sup>a</sup>Balliol College and Nuclear and Astrophysics Laboratory, Keble Road, Oxford OX13RH, UK and IN2P3-CNRS, Universités Paris VI et VII, 4 pl Jussieu, T33-RdC, 75252 Paris, France

In high centre-of-mass energy lepton-nucleon collisions the space-time time resolution of partonic processes can be *fine-tuned* within a dynamical range which is unattainable in hadronic collisions. Replacing nucleons by nuclei of variable atomic number enables one to tune the strength of colour forces. The experimental program of high energy electron-nucleon and its extension to electron-nucleus collisions should thus give an unique opportunity to experimentally explore the transition between the soft and hard interactions of small and extended partonic systems. Such an experimental program, which can be realized at DESY and/or BNL with relatively modest cost, is discussed in this talk<sup>1</sup>.

## 1. Introduction

The space-time charge resolution of the leptonic probe depends upon the following three kinematical variables:  $x_{Bj}$  - the invariant Bjorken variable,  $Q^2$  - the invariant 4-momentum of the exchanged photon ( $W, Z$  boson) and  $s$  - the centre-of-mass energy. These variables can be expressed in terms of the incoming and outgoing lepton 4-momenta  $k$  and  $k'$  and by the 4-momentum of the nucleon  $p$ :

$$\begin{aligned} Q^2 &= -q^2 = -(k - k')^2 \\ x_{Bj} &= Q^2/(2pq) \\ s &= (p + k)^2 \end{aligned}$$

In the plane perpendicular to the collision axis the constituents of hadronic matter carrying electro-weak charges can be resolved within the distances of  $l_t \approx 1/Q$ . The corresponding space-time resolution in the longitudinal direction is determined by the value of the invariant Bjorken variable -  $x_{Bj}$  and by the value of the reference frame-dependent Lorenz-factor of the nucleon (nucleus) -  $\gamma$ :  $l_l \approx t \approx 1/(2\gamma M x_{Bj})$ . In high energy collisions  $l_l$  and  $t$  are strongly correlated:  $(t - l_l) \approx 1/s$  simplifying the large-distance structure of hadronic matter to “frozen configurations”.

Strong interactions provide natural scales for the resolution of transverse distances:  $1/\Lambda_{QCD}$  and the inverse mass of the  $\rho$  meson,  $1/m_\rho$ . Using these yardsticks three kinematical regions can be defined:

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- the photo-production region (PR) ( $Q^2 < \alpha_1 \Lambda_{QCD}^2$ ) where the large-distance structure of hadronic matter is of importance and where the quasi-real photon interacts with the hadronic matter predominantly via the vector-meson component of its wave function.
- the transition region (TR) ( $\alpha_1 \Lambda_{QCD}^2 < Q^2 < m_\rho^2/\alpha_2$ ) where a direct coupling of the photon ( $W, Z$  boson) to a charged parton becomes important
- the deep inelastic region (DIS) ( $Q^2 > m_\rho^2/\alpha_2$ ) where the direct coupling of the photon to a charged parton dominate

These kinematical regions have rather fuzzy boundaries corresponding to  $\alpha_1$  and  $\alpha_2$  values in the range of approximately 0.1-1.0.

The natural scales of the resolution of the longitudinal distances in electron-nucleon and electron-nucleus collisions are: the size of nucleons  $R_N$  and size of nuclei  $R_A$  defined here in a Lorenz-invariant way as distances over which the valence quarks of the nucleon (nucleus) are localised. These values define three kinematical regions:

- large  $x_{Bj}$  region ( $x_{Bj} > 1/(2MR_N) \approx 0.1$ ) where the photon ( $W, Z$  boson) interaction with the nucleon (nucleus) is localised within the longitudinal distances smaller than the nucleon size
- intermediate  $x_{Bj}$  region ( $1/(2MR_A) \approx 0.01 < x_{Bj} < 1/(2MR_N) \approx 0.1$ ) where the photon interacts coherently within the longitudinal distances exceeding the size of the nucleon
- small  $x_{Bj}$  region ( $x_{Bj} < 1/(2MR_A) \approx 0.01$ ) where the light-cone-coherent interaction of the photon extends over the longitudinal distances exceeding the size of the nucleus

The  $(x, Q^2)$  region accessible to the HERA and earlier fixed target experiments is shown in Fig. 1. The main distinction between the fixed target and the collider kinematical domains, resulting from the different centre-of-mass energies, is that in the latter case the small  $x_{Bj}$  region can be studied in DIS regime where the relevant hadronic degrees of motion are quarks and gluons. In addition, the HERA collider experiments extend the measured DIS region to the  $Q^2 > M_W^2$  values where the Neutral-Current and Charged-Current processes are of comparable strength.

The small  $x_{Bj}$ , large coherence length, DIS processes can be viewed in two equivalent and complementary ways. In the Bjorken reference frame in which the nucleon (nucleus) moves with asymptotically large momentum the photon can be considered as colliding with delocalised partons, which are described by the light-cone wave function of the nucleon (nucleus). In this picture nuclei can be considered as sources of variable ( $A^{1/3}$ -dependent) strength of the colour fields. The quark and gluon interaction dynamics is expressed in this frame in terms of effective partonic densities in the nucleon (nucleus).

In the rest frame of the nucleon (nucleus) the small  $x_{Bj}$  DIS collisions can be viewed as coherent scattering of various quark-gluon Fock components of the virtual photon wave function. In this picture nuclei can be considered as effective ( $A^{1/3}$ -dependent) filters of

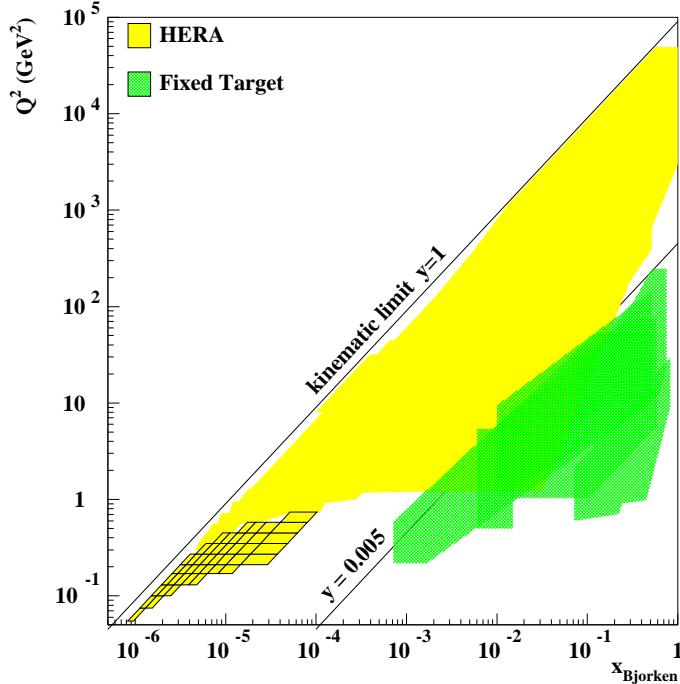


Figure 1. The kinematical region covered by HERA and fixed target electron-proton scattering experiments.

various Fock projections of the virtual photon wave function. The dynamics of quark and gluon interactions is expressed in this frame in terms of the cross sections for interactions of  $q\bar{q}$ ,  $q\bar{q}g$  and other Fock states of the virtual photon with the nucleon (nucleus).

## 2. Comments on the present HERA program

The experimental program carried out presently at HERA is more exciting than one might think while reading the papers and listening to the conference presentations of the results approved for public release. The relevance of the HERA electron-proton scattering program and the importance of its extension to electron-nucleus collisions for studies of strong interactions can be seen more clearly if one re-formulates research goals from a perspective which is different from the HERA orthodoxy.

The change of perspective boils down to using the QED processes and the hard perturbative QCD processes, which are theoretically well understood and cross-measured at  $p\bar{p}$  and  $e^+e^-$  collisions, as tools to investigate the *QCD-vacuum* and the *medium* effects in large (as compared to the confinement scale) distance propagation of point-like and extended colour objects. Within such a perspective the role of what is considered to be the “physics signal” and what is considered to be the “measurement noise” are re-

versed. In more practical terms, instead of getting rid of such non-perturbative effects by “re-tuning” of the Monte-Carlo generators or by absorbing them into various sets of “structure functions” studies are focused on these effects.

The discovery of the rise of the proton  $F_2$  structure function at small  $x_{Bj}$  [1] provided experimental evidence of striking differences in “large-friction” propagation of quarks in the “sticky” QCD medium with respect to a “frictionless” propagation of electric charges in “almost-transparent” QED media. In the published analyses of the structure function data [2], [3] these effects are absorbed into the effective gluon distribution derived in the the QCD analyses of the proton structure function within the framework of the DGLAP evolution equations. The questions if such a procedure is justified down to low  $x_{Bj}$  and if the medium dependent effects can be neglected are open. Changing the medium in which the photon couples to partons (replacing nucleons by nuclei) provides the most straightforward way to factorise out the medium effects and to verify the applicability of the DGLAP equations to the large density partonic systems.

One of the most striking medium effects observed at HERA is the difference in the fragmentation of the quarks ejected from the proton in DIS processes with respect to the fragmentation of quarks produced in  $e^+e^-$  annihilation processes [4]. The Breit-frame spectrum of charged hadrons produced in fragmentation of low  $x_{Bj}$  quarks is incompatible with the corresponding spectrum measured in the  $e^+e^-$  annihilation. In addition, the observed pattern of energy deposition in the direction of the current low  $x_{Bj}$  quarks deviates significantly from that of the large  $x_{Bj}$  quarks [5]. These observations indicate clearly that the medium induced effects of quark-energy-loss and quark-multiple-scattering are large and can be studied quantitatively in a future electron-nucleus scattering program.

The large fraction of rapidity gap events observed in low  $x_{Bj}$  DIS scattering [6] was unexpected and remains a mystery if one believes in the validity of the DGLAP evolution equations in this region. The conventional way of analysing these events within the Regge phenomenology boils down to absorbing rather than explaining the source of these events into the pomeron and reggeon structure functions. Studies of rapidity gap events in electron-nucleus scattering are indispensable in understanding universality of various de-excitations modes of the QCD vacuum.

### 3. Electron-nucleus scattering at high energies

High-energy electron-nucleus collisions were discussed at several workshops [7], [8], [9]. Physics highlights of the  $eA$  experimental program include:

- studies of the large density partonic systems and searches for nonlinear QCD phenomena
- studies of partonic structure of the large distance colour singlet excitations of the QCD-Vacuum
- filtering out soft from hard processes for perturbative QCD studies
- understanding of colour transparency and colour opacity
- studies of the space-time structure of strong interactions using the nucleus as a femto-vertex detector

- studies of luminous photon-photon scattering

In addition  $eA$  collisions provide precision measurements of partonic distributions in nuclei in the  $x_{Bj}$  range of  $10^{-4} - 10^{-1}$  and precise understanding of the high  $E_T$  quark-jets which can be used as probes of nuclear medium. They may turn out to be vital in pinning down the quark-gluon plasma signals in the forthcoming analyses of the RHIC and the LHC-AA data.

In an optimal scenario the atomic numbers of ions selected for the  $eA$  collisions should cover uniformly the  $A^{1/3}$  range (e.g  $D_2$ ,  $O_{16}$ ,  $Ca_{40}$ ,  $Sn_{120}$  and  $Pb_{207}$ ) and the collected luminosities should satisfy the condition:  $L^{eA} \times A \geq 10 \text{ pb}^{-1}/\text{ion}$ . The shopping list of measurements which can be made if the above criteria are fulfilled include:

- $F_2^A$  and  $F_L^A$  structure functions: inclusive and tagged by the number of wounded nucleons and evaporation fragments
- A-dependence of the gluon distribution
- Jet spectra and single particle inclusive spectra in the photo-production, DIS, and the transition regions
- A-dependence of the vector meson production
- A-dependence of the open charm and beauty production
- A-dependence of the fraction of rapidity gap events
- A-dependence of jet profiles and jet energy loss
- Fragmentation spectra of tagged low- $x$  partons in nuclear medium, also in correlation with the observed number of wounded nucleons and evaporation fragments
- Particle multiplicities and particle correlations in  $\gamma^* A$  and  $\gamma A$  scattering
- Bose-Einstein correlations and their A-dependence

Electron-nucleus collisions can be realized at DESY and/or at BNL. Preliminary machine studies presented by J. Maidement at the “Physics with HERA as an  $eA$  collider” workshop show that with relatively modest investment (ion source, RFQ) isoscalar nuclei of the energies of  $410 \times A$  GeV can be accelerated and stored at HERA providing luminosities:

- $L_{eA}^{HERA} \times A = (0.5 - 1.0) \times L_{ep}^{HERA} \approx 100 \text{ pb}^{-1}/\text{year}$  for electron - deuteron collisions
- $L_{eA}^{HERA} \times A \approx 1/6 \times L_{ep}^{HERA} \approx 20 \text{ pb}^{-1}/\text{year}$  for electron - oxygen collisions

In order to collide electrons with heavier nuclei a purpose-built heavy ion preinjector system is needed. For electron - lead collisions the expected luminosity is:

- $L_{eA}^{HERA} \times A \approx (1/20 - 1/50) \times L_{ep}^{HERA} \approx 3 - 7 \text{ pb}^{-1}/\text{year}$ .

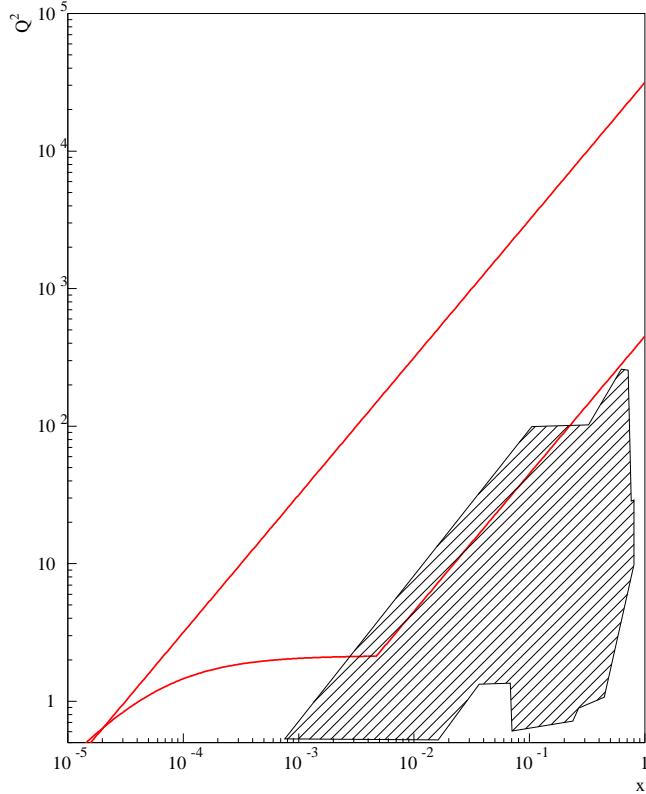


Figure 2. The kinematical region covered which can be covered in electron-nucleus collisions at HERA. The hatched area corresponds to the region covered in the fixed target  $eA$  experiments.

At BNL, preliminary machine studies [10] show that it is feasible to collide heavy ions with electrons by building a purpose-designed room-temperature electron(positron) ring in the RHIC tunnel. As an example, the expected luminosity for eAu collisions is estimated to be:

$$\bullet L_{eA}^{BNL} \times A = 3.7 \times A \times 10^{29} \text{ cm}^{-2} \text{ s}^{-1} \approx L_{ep}^{HERA}$$

for collisions of 10 GeV electrons with  $100 \times A$  GeV ions.

The above luminosities indicate that the electron-nucleus program requires at least 2-4 years of  $eA$  collisions at HERA. It is worthwhile mentioning that the simultaneous storage of two or three types of isoscalar nuclei allows one to drastically reduce the systematic uncertainties of  $A$  dependent ratios of various observables to  $\approx 1\%$  level. Such a running mode is considered possible by the machine experts at HERA.

What could be the time-schedule for such a program? If the BNL and/or DESY  $eA$  projects are approved by the year 2002, the first electron-ion collisions can be observed in 2005. For HERA, the  $eA$  collisions would follow the “high lumi” program which is expected to start in 2001.

Two possible detector scenarios are being considered. The first consists of building a dedicated detector for  $eA$  collisions. An alternative, cost-effective solution is to use the existing detector(s) upgraded for the  $eA$  runs.

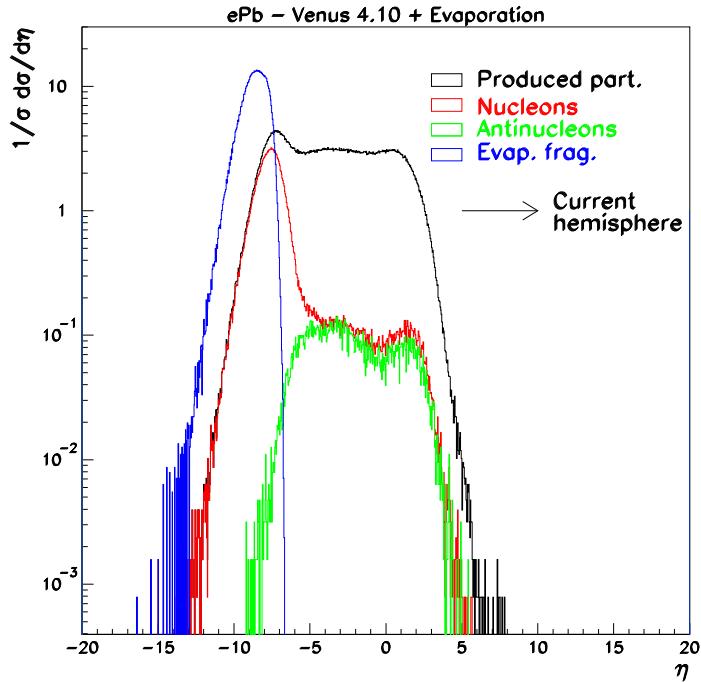


Figure 3. Pseudorapidity distribution of particles produced in electron-lead DIS scattering - Monte-Carlo studies.

The  $(x, Q^2)$  coverage of the existing HERA detectors for collisions of 27.6 GeV electrons with ions accelerated to the energy of 410 GeV/nucleon is shown in Fig. 2. The  $Q^2$  region which can be measured by these detectors is limited by the angular coverage of the central detectors. Note, that both HERA detectors [11] provide measurements of the energies and angles of electrons and photons emitted collinearly with the incoming electron. Consequently, the photoproduction events can be tagged and radiative processes can be experimentally controlled within the present detector set-up at HERA.

In Fig. 3 the pseudorapidity spectrum of particles produced in collisions of electrons with lead nuclei is shown. The present HERA detectors cover the pseudorapidity range down to  $\eta \approx -3.5$ . Below this pseudorapidity value the produced particles (mostly nucleons and nuclear fragments) remain undetected. This region is particularly interesting both for  $ep$  and  $eA$  collisions and the upgrade of the existing detectors to detect these particles is indispensable for the future experimental program.

#### 4. Conclusions

Over the last 20 years we have witnessed impressive experimental and theoretical progress in understanding the point-like structure of hadrons and in understanding short-distance processes involving quarks and gluons. Understanding the role of quarks and gluons in large-distance, soft processes remains one of the most important challenges for the coming decade. Electro-weak probes of tunable space-time resolution applied to hadronic media of tunable colour force strength provide an “adiabatic approach-path” to large-distance processes. The experimental program of high energy electron-nucleus scattering, which can address these challenges is exciting, feasible and cost-effective. It can be realized with relatively modest modifications of the existing accelerators at DESY and/or BNL, but needs a joint-effort of the particle and nuclear physics communities.

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